GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L15107, doi:10.1029/2008GL034132, 2008

Thermal electron periodicities at $20R_S$ in Saturn's magnetosphere

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Received 23 March 2008; revised 21 May 2008; accepted 11 June 2008; published 13 August 2008.

[1] Cassini fields and particles observations show clear evidence of periodic phenomena in Saturn's magnetosphere. Periodicities have been observed in kilometric radio emissions, total electron density (in the inner magnetosphere), magnetic fields, and energetic particles (in the outer magnetosphere). In this letter the first analysis of periodicities in thermal electron densities in Saturn's outer magnetosphere are presented. Plasma sheet electron densities and temperatures at 20 ± 2 R_S in Saturn's magnetosphere are studied and examined as a function of SLS3 longitude. Evidence for a density minimum at 170° is presented which is in excellent agreement with total electron density results in the 3–5 R_S range. The density asymmetry is interpreted as the result of a periodic plasma sheet motion where the northward offset of the plasma sheet varies with longitude hence producing a density modulation in the equatorial plane. The effect of magnetospheric compressions on the dayside density asymmetry are discussed. **Citation:** Arridge, C. S., N. André, N. Achilleos, K. K. Khurana, C. L. Bertucci, L. K. Gilbert, G. R. Lewis, A. J. Coates, and M. K. Dougherty (2008), Thermal electron periodicities at $20R_S$ in Saturn's magnetosphere, *Geophys. Res. Lett.*, *35*, L15107, doi:10.1029/2008GL034132.

1. Introduction

[2] Saturn's internal magnetic field is famously axisymmetric and hence a priori one would not expect magnetospheric periodicities, as observed at Jupiter for example. However periodicities in fields and particles in Saturn's magnetosphere were first detected in kilometric radio emissions (SKR) detected by the radio science experiment on Voyagers 1 and 2 [*Carr et al.*, 1981]. Despite the symmetry of the internal field, the 10.5-hour periodicity of these emissions was rapidly adopted as the rotation period of Saturn's deep interior. Subsequently, it was shown that this period isn't constant [e.g. *Galopeau and Lecacheux*, 2000] and so the period cannot represent the rotation rate of Saturn's deep interior. Recently a longitude system (SLS3) has been constructed which can be used to organize phenomena with respect to the modulation in SKR. This takes into account the variable period of SKR and builds on an earlier system (SLS2) *Kurth et al.* [2008, and references therein].

[3] A number of studies based on data from the Pioneer and Voyager spacecraft showed that the in situ fields and particles were also modulated at a period close to that of SKR [e.g., *Espinosa et al.*, 2003; *Carbary and Krimigis*, 1982]. Recent studies based on data from Cassini have shown a similar modulation with SKR, despite the apparent drift in the SKR period. *Gurnett et al.* [2007] showed that the density in the inner magnetosphere, between 3 and 5 R_S, varied by a factor of two between $\sim$330° and $\sim$150° in the variable longitude system. *Carbary et al.* [2007b] studied energetic particle measurements beyond 20 R_S (where 1 R_S = 60268 km) and found that the count rates from 28–330 keV electrons and 2.8–236 keV proton and oxygen ions were modulated at a period between 9.5 and 12.5 hours consistent with an anomaly rotating at 10.80 hours.

[4] Cassini-era magnetic field observations have confirmed the findings of *Espinosa et al.* [2003] and have shown that the field of the external magnetospheric currents is modulated at a period close to that of SKR [e.g., *Andrews et al.*, 2008]. The phase relationship between different components of the field has been emphasized by *Southwood and Kivelson* [2007] who have shown that inside 15 R_S, in the so-called "cam" region, the radial and azimuthal magnetic field components have a 90° phase difference but beyond 15 R_S in the magnetodisc they have an anti-phase relationship.

[5] Several models have been constructed to explain the plasma and field periodicities in the outer magnetosphere which all invoke a mechanism to generate vertical plasma sheet motions in an inertial reference frame. *Carbary et al.* [2007a] suggested that the warping of Saturn's magnetosphere combined with an inner magnetospheric anomaly would effectively periodically "shake" the outer magnetospheric plasma sheet thus providing a mechanism to vertically move the plasma sheet. *Southwood and Kivelson* [2007] discuss a system of field-aligned currents which produce the observed cam field in the inner magnetosphere and produce an effective dipole tilt in the outer magnetosphere. K. K. Khurana et al. (Sources of rotational signals in Saturn's magnetosphere, submitted to *Journal of Geophysical Research*, 2008) have developed a conceptual model in which the interaction of a longitudinally asymmetric lobe field (caused by a partial ring current), with the solar wind flowing around a tilted magnetosphere, produces an asymmetric lift effect which generates vertical motions.

[6] In this study we present the first analysis and identification of periodicities in thermal electron densities in Saturn's outer magnetosphere. Since our primary interest was the possible effect on Titan's magnetospheric interac-

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0094-8276/08/2008GL034132$05.00

tion we restricted our attention to the vicinity of Titan's orbital distance. In this paper we restrict our attention to describing the identified periodicity and possible interpretations. The consequences for Titan's magnetospheric interaction will be reported separately.

2. Data Processing and Analysis

[7] Intervals of the Cassini spacecraft's tour within ±2 R_S of Titan's semimajor axis (20.3 R_S) and within ±1 R_S of Saturn's rotational equator were selected for further analysis providing that they did not include a targeted Titan encounter or a magnetosheath excursion. These data selection criteria produced a set of 16 passes through 20 R_S covering the period from 18 February 2005 to 1 December 2006 inclusive. The trajectory of the Cassini spacecraft produced a minor local time bias to the dataset, with six passes in the dawn (3–9) and midnight (21–3) sectors, compared with four in the noon (9–15) sector. No passes through the dusk sector met our criteria.

[8] Electron moments were estimated by numerically integrating over the electron distribution measured by the central anode of the CAPS electron spectrometer, from 0.5 eV to 26 keV, assuming an isotropic electron distribution [*Lewis et al.*, 2008]. The spectra were averaged over the 4 minute actuation cycle of the instrument to remove variability caused by possible anisotropic distributions, and were background subtracted before integration. Magnetometer data was also analyzed with the electron moments to provide context for the plasma observations – for a more detailed description and analysis of magnetic field measurements near Titan's orbit, the reader is referred to C. L. Bertucci (Characteristics and variability of Titan's magnetic environment, submitted to *Philosophical Transactions of the Royal Society A*, 2008).

[9] Figure 1 presents electron and magnetic field observations for one of the passes identified using the criteria above. Maxima in electron flux and density are observed near 330° SLS3 longitude. An inspection of the magnetic field profile shows that in the low-density sector the field is quiet and largely in the radial and azimuthal directions. In the sector with enhanced particle flux the field is more disturbed (consistent with immersion in a plasma sheet) and more dipolar (the B_θ component becomes more dominant). This latter point is highlighted by the ratio $|B_r/B_\theta|$ which tends to unity in the high flux sector. Using the radial field component as a proxy for the distance to the center of the current sheet we assume a Harris neutral sheet profile and calculate the distance to the center ($z - z_0$) normalized by the sheet thickness, H. From this analysis it can be seen that the spacecraft is closer to the sheet center in the high flux sector, and further in the low flux sector. Thus the periodicity corresponds to a periodic motion of the spacecraft towards and away from the plasma sheet, and hence implies that the location of the plasma sheet is not static, but varies with longitude.

[10] Analyzing each pass showed generally lower densities in the 90–270° SLS3 sector, and generally higher densities in the 270–360° and 0–90° sectors. The lower densities were sometimes near the noise level for the ELS instrument and are often coincident with quiet, lobe-type magnetic fields in this longitude range. Figure 2 shows the distribution of electron density and temperature measurements as a function of SLS3 longitude for all the passes included in our sample. Typical electron temperatures at 20 R_S in Saturn's magnetosphere are 100–200 eV as can be seen in Figure 2. In Figure 2 we also show the distribution of $|B_r/B_\theta|$ which confirms the vertical motion picture identified in Figure 1.

[11] To identify the SLS3 longitude corresponding to the lowest density we binned the data by longitude and fitted a simple function to the binned density data. The function was parameterised by three values: n_0 the maximum density, n_a the amplitude of the density variation, and λ_0 the longitude corresponding to the minimum density.

$$n(\lambda_{SLS3}) = n_0 - n_a \cos^2\left(\frac{\lambda_{SLS3} - \lambda_0}{2}\right) \tag{1}$$

[12] Best-fit values for these parameters were determined using a non-linear parameter search using the Marquardt algorithm [*Bevington and Robinson*, 1992] where χ^2 was weighted according to the variance in each bin. Best-fit values of $n_0 = (1.0 \pm 0.3) \times 10^5$ m^{-3}, $n_a = (7.5 \pm 4) \times 10^4$ m^{-3}, $\lambda_0 = 170° \pm 20°$ were obtained using a bin size of 10°. Varying the bin size between 5° and 30° did not change the best-fit values by an amount larger than the uncertainty on each parameter. The minimum density longitude of 170° is in good agreement with that identified by *Gurnett et al.* [2007] in the inner magnetosphere (~155°). This fitted curve is also plotted in Figure 2.

[13] Figure 3 shows a set of five passes used in our study as a function of SLS3 longitude. The top four panels show all four passes through the noon sector (Cassini inbound passes on revolutions 4, 15, 18 and 19) and the last panel shows a representative pass through the midnight sector. *Arridge et al.* [2008] have shown that when the solar wind pressure is high, the dayside field configuration is quasi-dipolar, but under more expanded conditions the field stretches out into a thin magnetodisc current sheet. The field configuration during the five passes in Figure 3 is indicated in the top left of each panel.

[14] Amongst the four dayside passes there were two when the field configuration was a magnetodisc and two when the field was quasi-dipolar. In both the revolution 18 and 19 passes a magnetodisc was present and the periodicity is quite evident. The case during quasi-dipolar conditions is not as clear with almost no periodic features evident in the rev 4 inbound pass. Hence the upstream conditions (using the configuration of the magnetic field as a proxy) appears to have an effect on how the periodicities are expressed in the noon sector.

3. Interpretation and Discussion

[15] The magnetic field and electron data shows that Cassini moves vertically in and out of the plasma sheet thus producing an apparent density modulation. Hence we interpret these data in terms of a periodic vertical motion of the plasma sheet, alternately carrying the spacecraft from the low-density lobes, to the high-density plasma sheet, and back into the lobes. Therefore, the model (equation (1))

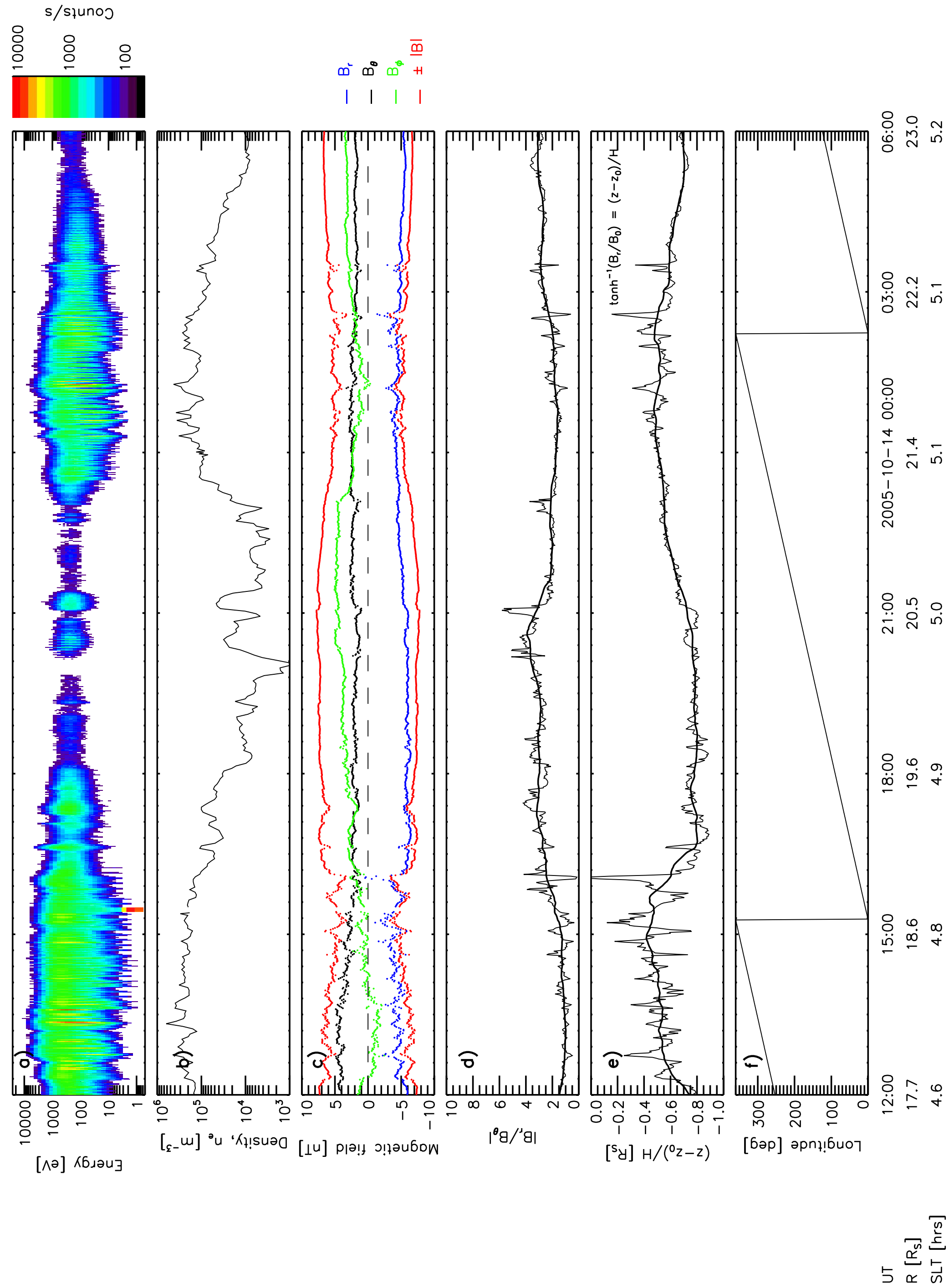

Figure 1. Thermal electrons and magnetic fields for 13/14 October (286/287) 2005: (a) time-energy electron spectrogram; (b) electron number density; (c) magnetic field in spherical polar (KRTP) coordinates; (d) the ratio of the radial to theta component, which increases when the spacecraft moves away from the plasma sheet; (e) the distance from the center of the plasma sheet, normalised by the plasma sheet thickness assuming a Harris-like profile for the radial field component; and (f) the sub-spacecraft SLS3 longitude. Figures 1d and 1e also contain 60-minute averages of each parameter to indicate average behavior.

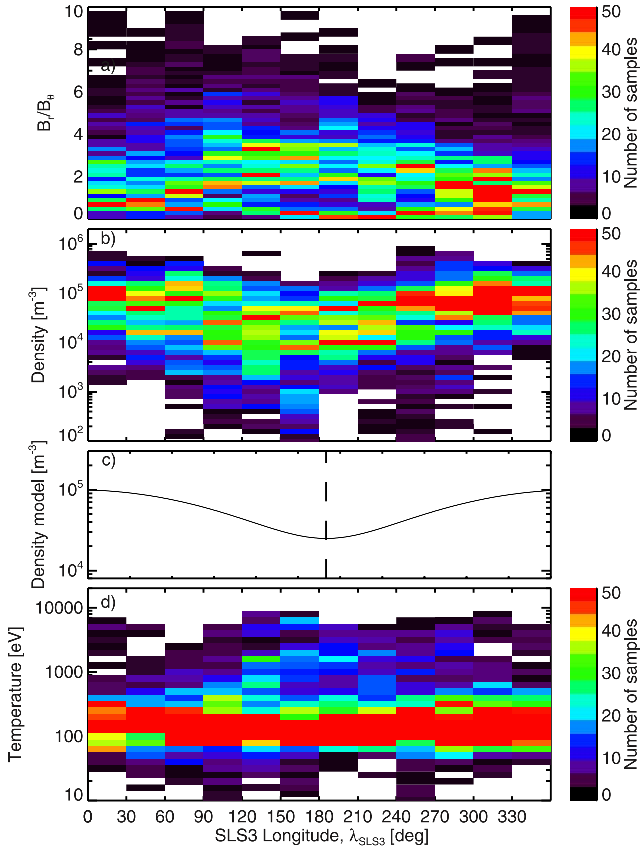

Figure 2. Distribution of five-minute electron density and temperature as a function of SLS3 longitude compared with the model density asymmetry from equation (1), and the ratio B_r/B_θ which is indicative of distance from the plasma sheet.

does not represent a static longitudinal density asymmetry in the plasma sheet rest frame.

[16] We noted from Figure 3 that the periodicity was only weakly present on the dayside when the field configuration was quasi-dipolar. We now consider three explanations for this effect. The first is that the northward dayside warping varies with solar wind dynamic pressure, either shifting the mean location of the sheet, or lessening the vertical oscillations. However, the physics of Saturn's dayside warping are not sufficiently well understood to address this. A second possibility is that the underlying periodicity is somewhat suppressed during quasi-dipolar conditions. However, the periodicity is quite clear in the inner magnetosphere where the field is strongly dipolar so this seems unlikely. The third possibility is that the electron scale height is larger when the field has a quasi-dipolar configuration, hence that a given oscillation amplitude may not cause a significant density modulation. We can address this by considering the centrifugal scale height in stretched field geometry. Equation (A1) derived in Appendix A shows that as the field becomes more dipolar the scale height increases, thus thickening the sheet in agreement with the above conjecture.

[17] Examining the density variations produced by a sinusoidal varying plasma sheet location combined with a simple Harris-like $sech^2(z/H)$ plasma sheet density profile allows us to reproduce density asymmetries similar to those observed. Reducing the oscillation amplitude and thickening the sheet can change the peak-trough density amplitude by factors of two or three. Hence we suggest that changes to the plasma sheet thickness and the oscillation amplitude primarily drive the qualitatively different dayside periodicities under quasi-dipolar and magnetodisc conditions.

4. Summary

[18] In this paper we have examined plasma sheet thermal electron number densities and temperatures at $20 \pm 2\ R_S$ in

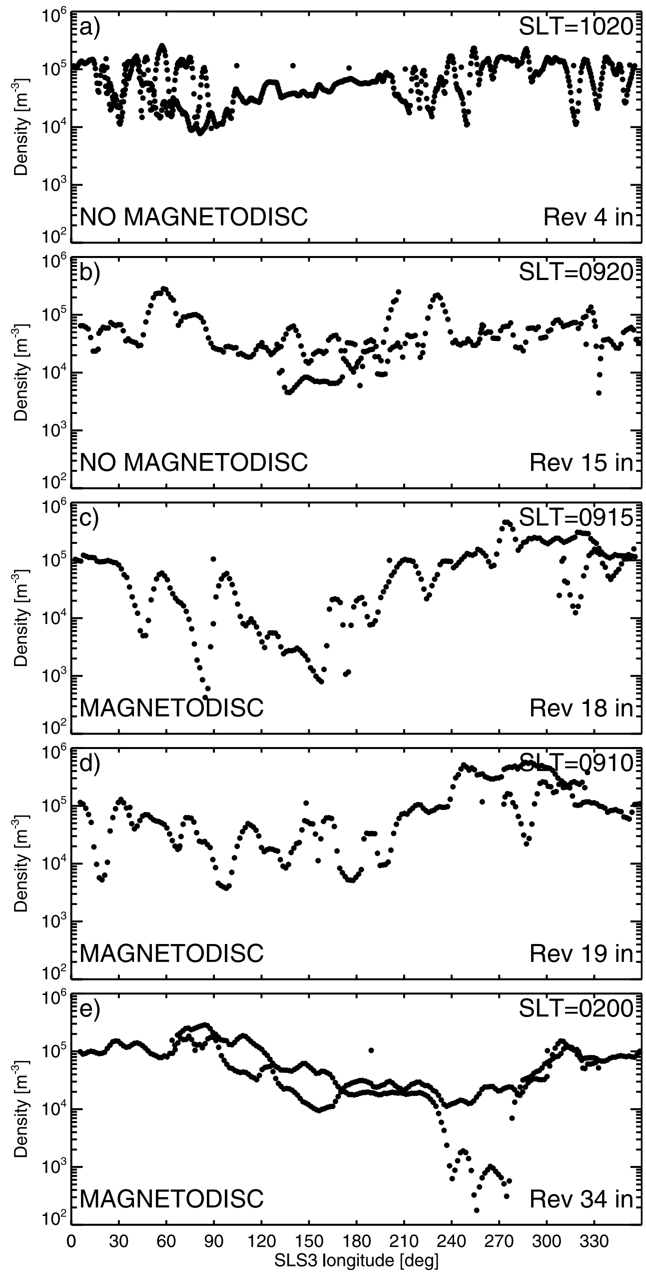

Figure 3. Electron number density as a function of SLS3 longitude for five passes in our dataset: (a–d) data for passes on the dayside and (e) a panel from the nightside for comparison. Annotation in each panel shows the actual Cassini revolution and direction (inbound or outbound), whether a magnetodisc was detected or not, and the Saturn Local Time during the pass.

Saturn's magnetosphere and have studied their relationship to the new longitude system (SLS3) proposed by *Kurth et al.* [2008]. We have identified a longitudinal asymmetry in both the number density and temperature with a minimum in density occurring at λ_{SLS3} = 170° ± 20° in close agreement with the density asymmetry in the inner magnetosphere reported by *Gurnett et al.* [2007]. This periodicity is associated with changes in magnetic field configuration consistent with a periodically varying spacecraft magnetic latitude; hence we interpret these observations in terms of the plasma sheet location being offset from the equator by an amount which varies with SLS3 longitude. It is this offset that then produces the observed density modulation. A number of models have been produced which interpret the outer magnetospheric periodicities in terms of a periodically varying plasma sheet location [e.g., *Southwood and Kivelson*, 2007; *Carbary et al.*, 2007a; Khurana et al., submitted manuscript, 2008]. The interpretation of our results in terms of vertical plasma sheet motion is compatible with each of these models.

[19] The results reported here have important consequences for modeling and analysis of the interaction of Titan with Saturn's magnetosphere. The changes in thermal electron density and temperature imply periodic thermal pressure variations of up to three orders of magnitude, over half a Saturn rotation (~5 hours). The effect of this variability on Titan's magnetospheric interaction is as yet unexplored and will be reported in a separate publication.

[20] To extend this work to different radial distances and latitudes, the structure of the plasma sheet must be taken into account. This work is in progress and will be reported in a separate letter.

Appendix A: Centrifugal Scale Height in Current-Sheet-Like Geometry

[21] Following *Persoon et al.* [2006], we derive the centrifugal scale height for a stretched field configuration. The shape of the field line in cylindrical coordinates (r, z) is given by $r^2 = R_0^2(1 - z^2/2h_r^2)$ where h_r is a scale length for the field (small h_r for highly stretched fields) and R_0 is the equatorial crossing point of the field-line (L) [*Maurice et al.*, 1997]. The potential energy for a particle of mass m rotating at an angular frequency of Ω was then derived and substituted into Boltzmann's equation. This provided the following expression for the centrifugal scale height in units of R_S:

$$H^2 = \frac{2k_B T}{m\Omega^2 R_S^2} \frac{1}{R_0^2/2h_r^2 + 1} \tag{A1}$$

[22] From this expression it can be seen that the scale height decreases as the field becomes progressively more stretched and hence that the scale height will be larger during quasi-dipolar conditions. One may also reach a similar conclusion by considering the adiabatic compression of the magnetosphere and the resulting changes in flux-tube volume and plasma sheet pressure [e.g., *Southwood and Kivelson*, 2001].

[23] **Acknowledgments.** The authors acknowledge Steve Kellock and Peter Slootweg at Imperial College London for MAG data processing. C.S.A. acknowledges useful discussions with Geraint Jones and Anne Wellbrock. C.S.A. and A.J.C. were supported in this work by the STFC rolling grant to MSSL/UCL.

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